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Efficacy of Cultural Control Methods for Combating Herbicide-Resistant *Lolium rigidum**

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Abstract: Herbicide-resistant populations of annual ryegrass (*Lolium rigidum*) are estimated to affect crop production on about 5000 farms in southern Australia. In order to manage resistant populations, some farmers have adopted a two-to-three-year pasture phase which allows use of grazing by sheep, and non-selective herbicides to deplete the weed seed-bank. However, in low-to-medium rainfall zones, where financial returns from pastures are relatively low, farmers have generally combined cultural practices for weed management with the use of alternative herbicides, mainly trifluralin. Used singly, none of the currently available cultural techniques provides an adequate level of weed control. However, when used in carefully planned combinations, extremely effective ryegrass control can be achieved. Some of the important cultural practices for ryegrass control include delayed sowing (sometimes in conjunction with a shallow autumn cultivation); stubble burning; cutting the crop for hay or green manure, increased crop density and capture of weed seeds at harvest. Selection of crop species and cultivars with superior weed suppression potential is also receiving considerable attention.

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1 INTRODUCTION

Herbicides have been the main method of weed management in the developed world for more than twenty years. The market for crop-protection chemicals in the world now exceeds US$26 000 million, of which herbicides are the biggest sector, comprising 44% of the total.[1] Herbicides also hold the premier position among crop-protection chemicals in Australia, where farmers in the cropping regions spend typically A$30–80 ha^{-1} on herbicides for weed control.[2] Last year the total expenditure on herbicides in the cropping zone of Australia exceeded A$450 million (CRC Weed Management Systems, unpublished). This still represents only a part of the total annual cost of weeds to Australian agriculture, which has been estimated to be A$3·3 billion.[3]

Consequences of the heavy reliance on herbicides by Australian farmers are now apparent in the form of widespread development of resistance in annual ryegrass (*Lolium rigidum* Gaudin) and many other weed species.[4] In a farmer survey conducted in 1991, it was estimated that 4000–5000 farms across southern Australia had herbicide-resistant weed populations (Agricultural & Veterinary Chemical Association of Australia, unpublished).

In a more recent regional survey that covered more than 800 000 ha of the cropping area in South Australia, more than 40% of randomly selected fields were found to be infested with diclofop-methyl-resistant annual ryegrass.[5] The problem is also rampant in Western Australia, where bioassay tests over the last five years have

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confirmed resistance in more than 1000 ryegrass populations that had originated from more than 400 different farms (Gill, G. S., unpublished).

The rate of resistance development, particularly in *L. rigidum*, can be rapid. In situations where selection pressure is high and repetitive, high levels of resistance have been detected within four to five years.[6] This is consistent with the outputs of simulation models in which resistance is considered to be inherited as a single dominant gene.[7] In studies conducted so far, target site resistance to Acetyl CoA carboxylase (ACCase) and acetolactate synthase (ALS) inhibiting herbicides has been shown to be controlled by a single dominant gene.[8] However, in some ryegrass biotypes (e.g. SLR 31) several distinct resistance mechanisms, including 'membrane recovery response', enhanced herbicide metabolism and resistant ACCase, have been identified.[9] Such multiple mechanisms are likely to be complex and under the control of several genes. In addition to the rapid development of resistance, the presence of multiple resistance mechanisms in some ryegrass populations can give unpredictable cross-resistance to other herbicide groups with very dissimilar modes of action.[10]

Widespread development of resistance in several weed species has sharpened industry focus on integrated weed management (IWM). However, implementation of IWM needs considerably greater management input to achieve the end result that was previously obtained with a single herbicide application. There is a limited choice of field crops with suitable adaptation to the dryland Mediterranean environment experienced across much of southern Australia. Apart from pastures, other rotation options offer little additional value for weed management over cereals, and the weed control is heavily dependent on ACCase- and ALS-inhibiting herbicides.

In this paper we present information on various non-chemical management techniques that can be employed successfully for weed management. The focus of the paper will be *L. rigidum* (annual ryegrass) management, as this is still the most intractable weed over a very large cropping area of southern Australia. Data are presented from various papers published over the last twenty years, but, where necessary, data from unpublished research conducted by the authors have also been incorporated. Some of the information presented here has been made available to farmers in an extension publication, 'Resistance Management Manual'.[11]

2 MANAGEMENT OF RESISTANT WEED POPULATIONS

2.1 Pastures and resistant weed management

Legume-dominant pastures, a cornerstone of ley-farming in Australia, are valuable for improving soil fertility (nitrogen) and structure, which are beneficial to subsequent crop production. Pastures have also enabled farmers to manage troublesome crop weeds such as ryegrass by grazing management, particularly during the spring. Rotations based on pasture/wheat or pasture/wheat/fallow, that included several tillage operations, were practised routinely until the late 1960s in southern Australia. However, introduction of selective herbicides in the 1980s opened up opportunities for farmers to crop more intensively by controlling weeds within the crop year. This trend was accelerated further by the decline in wool prices forcing farmers to rely even more heavily on selective herbicides for weed control.

Annual ryegrass has a relatively short-lived seed bank.[12] Therefore, most of the plants that emerge in a crop come from the seed that was shed during the previous season. Consequently, management practices that prevent seed production during spring can have a large impact on the weed infestation in the subsequent crop.

2.1.1 Grazing management

Grazing animals can act as biological control agents in both pastures and crops, either within the crop itself or by reducing weed numbers or seed set in the preceding pasture or crop. Weeds may be more palatable than other species and therefore grazed harder, or they may be less capable of recovering from grazing.[13] Amor[14] pointed out that grazing by sheep is the main method of biological weed control on dryland farms in Victoria, and that sheep are used extensively to suppress weeds on fallows and, to some extent, to reduce the seed production of weeds in pastures before cropping.

Ryegrass was originally grown as a valuable pasture plant over large areas of southern Australia. It is a palatable species and sheep will readily graze it at all stages of its development. Consequently, grazing can be used as a management tool to minimise seed-bank replenishment. Grazing pastures at high stocking rates (15 sheep ha^{-1}) has been shown to result in large reductions (*c.* 80%) in ryegrass density in subsequent pastures[15] and crops.[16] In Western Australia, Pearce and Holmes[17] also reported large reductions (88–96%) in subsequent ryegrass density due to heavy grazing in the spring and during the flowering and seed production stages of the weed. However, later grazing, over summer, was relatively ineffective and reduced the ryegrass seed-bank by only 20%, because most (70%) of the seed produced had already shed and this component of the seed-bank was inaccessible to sheep for grazing.[18] Seeds that are ingested by the animals lose viability during the passage through the gut.[18]

Ryegrass control with grazing is reliant on having stocking rates capable of consuming spikes before seeds have reached maturity and shed to the ground. However, as the sheep population in Australia has declined substantially in the last six years, many crop-dominated farms no longer have adequate numbers of sheep to control weeds by grazing.

An effective grazing strategy that has received little attention involves the selective removal of pasture weeds by grazing animals (usually sheep) from a pasture containing a mildly unpalatable legume.[19] Work by MacNish and Nicholas[20] showed that both grasses and broad-leaf weeds were removed from a pasture containing subterranean clover (*Trifolium subterraneum* L.) cv. Dinninup while that containing other cultivars of similar maturity contained a significant component of weeds (Table 1). The very high clover content was maintained even at a low stocking rate where pasture availability was high. The yield of barley following pasture was negatively correlated with the grass content in the previous year with Dinninup pastures producing the highest barley yields. Apart from reduced weed competition, improved nitrogen fertility and the disease-break effect of legume-dominant pastures would have also contributed to the yield response. Field observations of livestock grazing Dinninup pastures indicate that animal growth rates are slightly lower in spring but the rates during the summer period are higher, reflecting superior quality of legume dry material (Nicholas, D. A., 1994, pers. comm.). With clear signs of long-term improvement in wool prices, there is a considerable scope to enhance the role of grazing in weed management in pasture-cropping rotations.

2.1.2 *Preventing weed seed set with 'spray-topping'*

Although it is possible to prevent weed seed production by heavy grazing (high stocking rate) in spring,[15–17] most farmers do not have adequate stock to graze the whole farm heavily. Furthermore, such heavy grazing can leave the fields bare and prone to erosion. The technique of 'spray-topping' or 'pasture-topping' combines the grazing effect of sheep with the application of a non-selective herbicide such as paraquat or glyphosate. Herbicides are sprayed at the anthesis to soft dough stage of grass weeds, followed by sufficient grazing pressure to prevent regrowth. Grazing management prior to herbicide application is also important for achieving uniform development of grass weeds at the time of spraying. The technique has undergone considerable on-farm evaluation in southern Australia and is now used widely on fields in pasture, particularly those targeted for cropping in the next season.

Pearce and Holmes[17] reported 29–80% reduction in seed production from five different field experiments conducted in Western Australia. The effectiveness of the technique was heavily dependent on the stage of development of the weed at the time of spraying, maintenance of adequate grazing pressure and rainfall events after the treatment. In a more recent study, an 85% reduction in ryegrass plant density was recorded following a spray-topping treatment with paraquat.[21] Figure 1 depicts the range of ryegrass control obtained in seven field experiments in Western Australia (Holmes, J. E. & Gill, G. S., unpublished). Performance of spray-topping varied widely, in this case from 35 to 93% with a median of about 60% (Fig. 1). Spray-topping prevents replenishment of the weed seed bank, as is also the case with heavy grazing but the grazing intensity required is much lower thus reducing the risk of soil erosion.

2.1.3 *Cutting for hay*

In spring, if pasture production is in excess of grazing demand, the sward can be cut and dried *in situ* for later consumption. If the cutting is undertaken at, or soon after, the flowering stage of ryegrass, then this technique can have a large impact on weed seed production. Reeves and Smith[16] recorded an 84% reduction in ryegrass density in a wheat crop following a pasture that was cut for hay in spring. Although cutting early will invariably give lower biomass yields, this is compensated for by improved hay quality.

2.1.4 *Burning pastures in autumn*

Burning pasture residues in summer can almost completely destroy the surface seed-bank of ryegrass.[16,21] However, in Australia, summer burns are illegal and an extreme hazard to the environment. The results from

TABLE 1
Spring Dry Matter Yields of the Components of Three Subterranean Clover (*Trifolium subterraneum*) Cultivars Grazed at Two Stocking Densities[a]

Clover cultivar	*Stocking rate*[b]	*Pasture components (kg ha^{-1})* Grass	Clover	Other	*Barley yield (kg ha^{-1})*
Seaton Park	L	230	1785	536	1930
Seaton Park	H	109	1092	619	2290
Daliak	L	324	804	96	2244
Daliak	H	633	1393	84	1848
Dinninup	L	0	3270	0	2932
Dinninup	H	0	1440	0	2675

[a] Adapted from Reference 20.
[b] L: low, 7·4 sheep ha^{-1}, H: high, 9·9 sheep ha^{-1}.

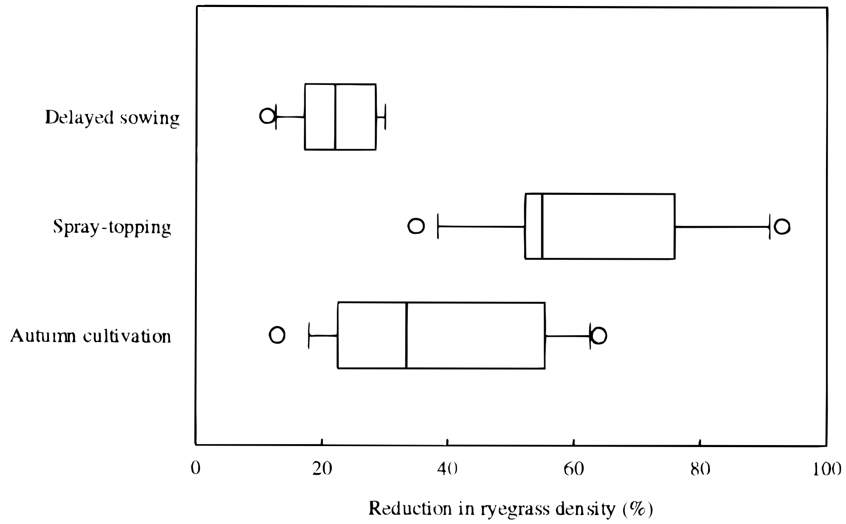

Fig. 1. A 'box and whiskers' diagram of the effectiveness of autumn cultivation (seven trials) and spray-topping pastures (six trials) in reducing ryegrass density (%) in the subsequent wheat crop. Results for delayed sowing (four trials) are expressed as reduction in ryegrass density (%) for each week's delay in sowing wheat. The boundary of the box closest to zero indicates the 25th percentile, the line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers on either side of the box indicate 90th and 10th percentiles. The hollow circles represent outlying points.

experiments with autumn burns of pasture have shown decreases in ryegrass density of 35–70%.[16] The seed that are buried are rarely affected by fire. To obtain high efficacy from burning, care should be taken to prevent burial of seeds (e.g. due to trampling by grazing animals) before the burn.[17] Pasture residues can also be burnt in autumn to destroy some of the weed seed-bank, resulting in 35–66% reduction in ryegrass density in the following season.[16,21] As with heavy grazing, there can be a considerable risk of soil erosion if burning is carried out on light-textured soils. Consequently, the majority of farmers do not regard burning to be consistent with sustainable agriculture.

2.2 Resistant-weed management in arable cropping systems

Due to absence of grazing animals and a much more restricted scope for use of non-selective herbicides, management of resistant weeds is a much bigger challenge in continuous cropping systems. Cultural practices for weed control that can be used within the arable cropping phase of the rotation are discussed below.

2.2.1 Stubble burning

Burning provides an opportunity to destroy weed seeds (including ryegrass) present on or near the soil surface. The efficacy of burning is dependent upon the location of the seed, ambient temperature and the amount of fuel available.[17,21] As in the case of pastures, crop fields designated for burning should not be grazed over summer to prevent the burial of weed seeds and also to maintain the maximum fuel level for the burn.

2.2.2 Autumn cultivation to stimulate weed germination

A shallow cultivation in autumn is aimed at improving soil–seed contact to obtain faster and more uniform germination of weed seeds with the onset of winter rainfall in order to maximise the pre-sowing weed kill.[22] The success of this technique is largely dependent on rainfall received after the initial cultivation.[23] The technique was commonly used by farmers until selective herbicides became widely used. Pearce and Holmes[17] reported 30–43% increase in ryegrass seedling emergence at two different locations in Western Australia following an autumn cultivation. In seven field studies (Holmes, J. E. & Gill, G. S., unpublished) over three seasons, autumn cultivation resulted in a 13–64% reduction in ryegrass plant density in the subsequent wheat crop (Fig. 1). Such a big range in response of ryegrass to this weed-control technique is likely to be due to variable environmental conditions encountered over different seasons and locations. Rainfall must occur after the cultivation to trigger germination and emergence of weeds. However, the frequency and intensity of rainfall events in autumn is highly variable, resulting in variable efficacy of autumn cultivation as a weed-management tool. Therefore, it is not surprising that farmers readily abandoned such inherently variable methods of weed control in favour of reliable selective herbicides.

2.2.3 Delayed sowing to maximise pre-sowing weed kill

Given adequate time after 'opening' rains (commencement date for growing season), most non-dormant weed seeds will germinate and can then be killed either by cultivation or with non-selective herbicides. Some field studies indicate that a substantial (*c.*

80%) ryegrass emergence takes place within four weeks after the opening rains.[12] Before selective herbicides became available, farmers routinely used to sow their crops about four weeks after the opening rains in order to deplete the weed seed-bank. In a recent study, Matthews and Powles[24] reported a 44–59% reduction in ryegrass density in crops when sowing was delayed by three weeks. In other field studies, an 11–30% reduction in ryegrass density in the crop was achieved with each week's delay in sowing (Holmes, J. E. & Gill, G. S., unpublished). The median response to each week's delay in sowing was surprisingly consistent at around 20% (Fig. 1).

However, benefits of delayed sowing in terms of improved ryegrass control have to be offset against reduced yield potential of the crop because of the shortened season available for crop growth. Over the last 10 years there has been a strong trend for farmers to improve yields by sowing early. Some of the data obtained from weed-free sites have shown a 15–50 kg ha^{-1} day^{-1} loss in yield due to delay in sowing.[25] Farmers are generally reluctant to delay sowing for weed control except on the weediest fields on the farm, which are often a consequence of herbicide resistance.

2.2.4 *Increased crop density for weed suppression*

The role of increasing crop density in reducing competitiveness and seed output by weeds has been reported in several studies.[26–28] Similar benefits of higher crop density have been reported from some studies undertaken in Australia. On black earth soils on the Darling Downs in Queensland, large reductions in wild oat biomass and seed production and a consequent increase in wheat grain yield due to increase in wheat density have been reported.[29] In a later study, Medd *et al.*[30] in New South Wales found that competitive effects of annual ryegrass on wheat were substantially reduced by increasing wheat sowing density.

In spite of promising research results, farmers in low-to-medium rainfall regions in particular, have been reluctant to increase their wheat plant density above 100–150 plants m^{-2}. There are concerns about the effect of higher plant densities on grain size and potential financial penalties due to increased levels of screenings (pinched grain) in the produce. However, such fears are not supported by any experimental evidence. For example, Medd *et al.*[30] found only 10–15% reduction in average grain mass as wheat density increased from 75 to 200 plants m^{-2}. In Western Australia, average grain size of wheat decreased by only about 5% with an increase in wheat density from 90 to 280 plants m^{-2} (Gill, G. S., unpublished). The level of screenings and grain protein content was also unaffected by increasing wheat density, but seed production by ryegrass was reduced by 80%.

2.2.5 *Selecting crop genotypes with superior weed suppression capacity*

Differences between cultivars in competitiveness with weeds have been shown to exist in different cereal species.[31–35] Australian wheat cultivars have also been investigated for competitiveness with weeds. Reeves and Brooke[36] studied 29 wheat cultivars for competitive ability against ryegrass and found that yield loss ranged from 23 to 48%. The five cultivars least affected by weed competition in this study were all tall in stature. None of the other measured traits explained competitiveness of the various cultivars examined. More recently, Lemerle *et al.*[37] showed considerable differences within a large collection ($n = 250$) of local and overseas wheat genotypes for competitive ability against annual ryegrass. There is clearly scope for selection and possibly also for breeding wheat cultivars for superior competitive ability against weeds in order to reduce dependence on herbicides in the future.

2.2.6 *Hay and green manure crops for depleting weed seed-bank*

Cutting the crop for hay or incorporating the residues into soil as a green manure prevents weeds from replenishing the seed-bank. Even in a more persistent weed species such as wild oat (*Avena* sp), a single fallow season could reduce the seed-bank by about 80% provided new seed return was prevented.[38] Similar, if not greater, effects of such a practice would be expected for ryegrass in which almost the entire seed-bank can be depleted in one year.[12] However, economic returns from hay production are extremely volatile and dependent on the proximity of the farm to markets. Farmers generally do not view hay production as a practical tool for resistant weed management. There is little published information on the effect of green manuring on weed management, but the magnitude of the effect is likely to be similar to that of cutting for hay. In our studies, green manuring with a lupin crop was found to reduce ryegrass density in the subsequent wheat crop by 67% (Gill, G. S., unpublished).

2.2.7 *Weed seed capture during the harvest*

Seeds of some weed species are held firmly by inflorescence structures well after maturity and even until the time of crop harvest. It has been estimated that in excess of 75% of ryegrass seeds produced in a season pass through the harvesting machinery, and are normally returned to the soil seed-bank.[21] Capture and removal of unshed weed seeds during crop harvesting has the potential to play an important role in an integrated system for the management of annual ryegrass. Matthews and Powles[24] in South Australia reported a 52% reduction in the ryegrass soil seed-bank due to capture of weed seeds during harvest. In Western Australia, Gill[39] recorded 60–80% removal of ryegrass seed

TABLE 2
An Example of Effective Weed Management Systems for the Control of Annual Ryegrass in a Pasture–Wheat Rotation

Treatment	*Ryegrass in crop*[a] (*plants* m^{-2})	*Wheat grain yield*[a] (*kg* ha^{-1})
1. Conventional (two cultivations, then sown)	535	1200
2. Conventional + autumn cultivation (in April)	296 (45)	1429 (16)
3. Conventional + previous pasture spray-topped	40 (93)	1984 (40)
4. Conventional + autumn cultivation + spray-topping	15 (97)	2123 (44)
5. Conventional + spray-topping + stubble burnt	9 (98)	2143 (44)
6. Conventional + autumn cultivation + spray-topping + stubble burnt	8 (99)	2232 (46)
7. Conventional + diclofop-methyl	10 (98)	1835 (35)
LSD ($P = 0{\cdot}05$)	95	233

[a] Values in parentheses are reductions in ryegrass density or increases in grain yield (%), relative to the conventional practice of two cultivations followed by sowing.
Note: Spray-topping carried out in previous pasture.

production which reduced weed infestation in the subsequent crop by 73%.

3 WEED MANAGEMENT SYSTEM (AN EXAMPLE)

In the absence of selective herbicides due to resistance, weed management demands a holistic approach requiring execution of several individual components to achieve a level of weed control which was previously possible with the single pass of a selective herbicide; this requires careful attention to detail and a considerably greater management input and expertise. An example of such a weed management system based on our research in Western Australia is presented in Table 2. It should be noted that, on this herbicide-susceptible population, appropriate combinations of cultural treatments gave levels of ryegrass control similar to that achieved with the application of diclofop-methyl. Higher yields achieved with the optimal combinations of cultural practices, as in this example, can offset the costs of the extra operations.

4 THE CURRENT SCENARIO

Due to the extensive scale of farming in Australia, it is difficult to imagine a situation where herbicides are not an important component of weed management. With the current episode of resistance to ACCase- and ALS-inhibiting herbicides, an overwhelming farmer response has been to switch to dinitroaniline herbicides which, at present, are rarely affected by resistance. However, due to the relatively lower efficacy of this herbicide group, farmers have been forced to complement herbicide efficacy with cultural methods of weed control, including delayed sowing, increased crop density, weed-seed capture during harvest and pasture-topping and grazing. 'Crop-topping', which refers to application of paraquat soon after the anthesis of ryegrass infesting grain legume crops, has also contributed to the management of resistant populations. When used at the correct stage of ryegrass development, crop-topping can give >90% reduction in its seed production (Gill, G. S., unpublished). This technique has become readily accepted by farmers because it is fast and no additional capital investment is required. Weed-seed capture equipment, on the other hand, can cost up to $20 000 and this additional expense appears to be a major impediment to the adoption of this technology.

Since 1982, when chlorsulfuron was released in Australia, no new herbicide groups with activity on ryegrass have been introduced. This has finally dampened farmers' optimism that new herbicides will solve the resistance problem. Consequently, integrated weed management has become a much more readily accepted concept which is being put into practice by farmers to varying degrees. There is a risk that release of herbicide-tolerant transgenic crops could revert agricultural practice to more reliance on herbicides.

There is little doubt that herbicides are extremely powerful selection agents and, with continued use, resistant populations will continue to evolve. The challenge for the entire industry is to detect resistance in its early stages of development and implement environmentally friendly alternative strategies that enable farm profitability to be maintained.

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